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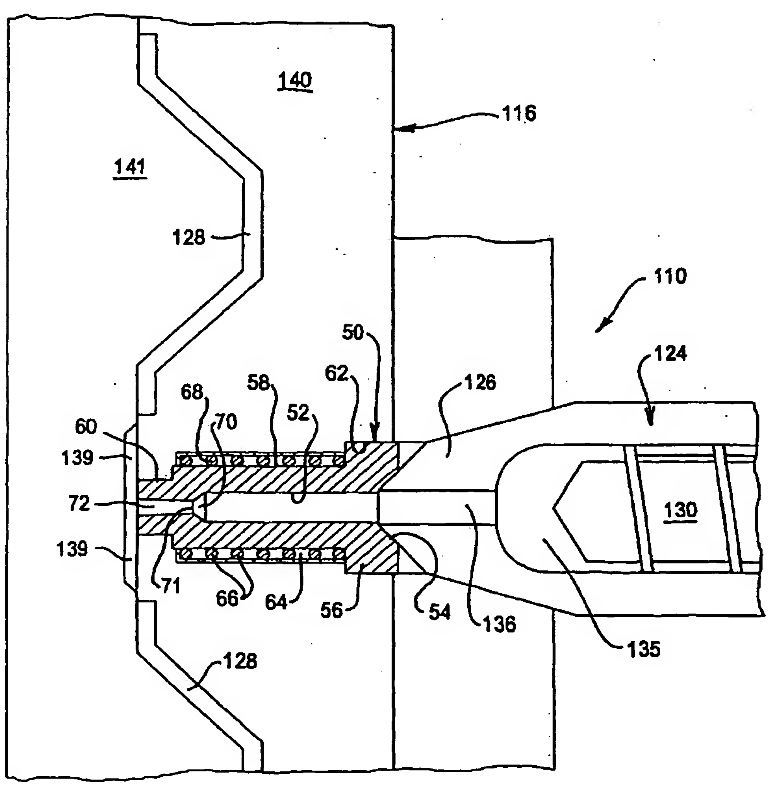
(54) Title: PROCESS AND APPARATUS FOR PRODUCING SHAPED METAL PARTS



(57) Abstract: A process for injection moulding of articles from an alloy able to form a dendritic primary phase includes providing at a nozzle a quantity of the alloy which is at least predominantly in a liquid state. The alloy is moved along a flow path from the nozzle to a die cavity defined by a mould whereby the alloy is caused to flow along the flow path as a stream of alloy. The alloy is controlled as it is moved along the flow path to increase the stream in transverse cross-sectional area along flow of the alloy between an inlet end and an outlet end of at least a part of the length of the flow path. This increase reduces the flow velocity of the alloy sufficiently in its flow through said part, from a sufficient flow velocity at the inlet end, whereby the alloy is caused to change from said at least predominantly liquid state to a semi-solid state. The die cavity is able to be filled with the alloy in the semi-solid state.

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PROCESS AND APPARATUS FOR PRODUCING SHAPED METAL PARTS

This invention relates to a process and apparatus for producing shaped metal parts, by casting alloys in a semi-solid or thixotropic state.

Over the last 30 years, there has been considerable interest in semi-solid metal casting and forging. Work on this has led to a number of processes, including those known as rheocasting and thixocasting. However such processes have not achieved major commercial success, relative to more conventional processes such as hot- and cold-chamber die-casting.

In initially developed semi-solid metal casting and forging processes, there is utilised a preformed ingot of an alloy having a specific microstructure. This microstructure is characterised by rounded or spheroidal primary particles, consisting of degenerate dendrites, in a lower melting point secondary phase or matrix. The preformed ingot is prepared by cooling a melt of the alloy to form a slurry while subjecting the melt to agitation, achieved for example by mechanical, or inductive electromagnetic, stirring. A balance is required between the shear rate resulting from the agitation and the solidification rate so that a thixotropic slurry is achieved. When a thixotropic slurry having a required ratio of solids to liquid is achieved, the alloy is cooled rapidly to produce the ingot having the required microstructure.

When the ingot is reheated to a suitable liquid-solid state, it still possesses thixotropic properties. In that state, it therefore is able to be cast or forged into a shaped metal part. It is found that force applied in the casting or forging transforms the properties of the thixotropic alloy to those more similar to a liquid, thereby facilitating the shaping to be achieved to attain the required form of the shaped article.

A factor which has limited the commercial acceptance of semi-solid metal casting and forging based on use of a preformed ingot is the added cost of producing the ingot. Also, while the ingot can have a relatively uniform required microstructure throughout the main part of its volume, there inevitably is a dendritic surface layer. In some cases, this layer needs to be removed, thereby adding to production costs. Alternatively, in casting or forging from the ingot, care has to be exercised to ensure that the material of the skin is not carried through to a part or product being produced, thereby limiting the form of mould able to be used. Additionally, the process requires purpose designed casting or forging

apparatus which can need modification if production is to change from use of ingots of one size to ingots of another size.

The Thixomat process is a development of such procedures. In this process, an ingot is reduced to chips or pellets. The ingot may be one prepared as described above, or it may be a conventional ingot. In each case, the chips or pellets are fed to the hopper of an injection machine similar in form and function to a plastics injection moulding machine. In the injection machine, the pellets are advanced by a rotatable extruder screw through a heating zone defined by an elongate barrel, to an injection nozzle which communicates with at least one die cavity defined by a die tool. The chips are heated as they are forcefully advanced through the barrel, partly by shear generated by the screw, so as to attain the thixotropic state, with the force generated by the screw causing the alloy to flow to an accumulation chamber immediately preceding the nozzle.

From the accumulation chamber, the alloy may be extruded through the nozzle and collected for use in a separate casting or forging operation. Alternatively, the alloy may be extruded through the nozzle into a transverse shot sleeve in which a ram is operable to force the alloy into a die cavity of a mould. In a further alternative, the screw may be advanced axially to force the alloy through the nozzle and into a die cavity of a mould in a direct injection operation.

The Thixomat process necessitates the very substantial cost of reducing ingots to chips or pellets. Also, if based on chips or pellets produced from a prepared ingot as described above, it also has an added cost in the production of the ingot. As initially conceived, the process also provided considerable difficulty in attaining and retaining a required temperature in which the alloy possesses the required thixotropic properties, a difficulty exacerbated by the relatively long residence time for which the alloy is progressed along the barrel. Also, even assuming the alloy possesses those properties when entering the accumulation chamber, the arrangement was not suited to the production of shaped metal parts which have a required, fine microstructure.

One form of a Thixomat type of process is disclosed in US patent 5040589 to Bradley et al. This process is for injection moulding of metal alloys and, in broad terms, the process is similar to that described above. Of relevance to the present invention, Bradley et al. discloses that, for the required injection moulding, alloy is displaced from the accumulation chamber by the screw being advanced at

a high linear rate (typically 50 to 190 in/s, i.e. 1.25 to 4.75 m/s), with a shot trace or profile of the screw velocity not being appreciably different from that resulting from high pressure die casting. There is no indication of resultant flow rates for the alloy, except for reference to examples in which a gate velocity of 800 in/s (20 m/s) was used. This gate velocity also is typical of conditions used in conventional pressure die casting. As a gate is a constriction through which a runner opens to a die cavity, it is evident that as also applies in conventional high-pressure die casting, a runner flow velocity somewhat lower than 800 in/s (20 m/s) was used.

An emphasis throughout the disclosure of Bradley et al. is on close control of alloy temperature as it is advanced along the barrel, and while it is in the accumulation chamber and in the nozzle bore. Six distinct heating zones are identified with four of these, covering the major part of the length of the barrel, varying in trials by only 3 to 5°C, depending on the particular magnesium alloy being used. No doubt this level of control can be maintained at least for a time. However, it clearly presents difficulties, and complicates ancillary equipment requirements for monitoring temperatures and controlling successive heaters. Also, maintaining the control and recommencing operation after an interruption can present difficulties. Moreover, even with such control, it is considered that the process still is not well suited to the production of parts possessing a fine microstructure.

The present invention is directed to providing a process which is similar to a Thixomat type of process, but which facilitates attainment of better quality casting without the complexity of the Thixomat process. However, in a highly preferred form, the invention provides a modified form of the Thixomat type of process and apparatus, which also does not require use of pellets or chips of preformed ingots which, when suitably heated, have semi-solid or thixotropic properties. That is, the present invention is operable with pellets or chips from any standard alloy, or with molten alloy having a solids content sufficient only to enable it to be advanced by a screw.

Our experience in producing shaped metal parts, by casting alloys in a semi-solid or thixotropic state, has established that the physical properties of the parts produced vary considerably with the solids content of the semi-solid or thixotropic alloy being cast. This variation in properties results from variation in

the microstructure exhibited by parts with variation in the solids content of the alloy being cast.

It is believed that at least in earlier forms of the Thixomat process, the solids-content generally can be less than about 30 volume % and, hence, low relative to the solids content of alloys used in other casting or forging processes based on preformed ingots. The low solids content of the Thixomat process possibly can be attributed to the relatively high heat energy input to the alloy resulting from the intense shear levels generated by the screw. A resultant excessive liquid content will enable growth of the degenerate dendrite or spheroidal primary particles, such that they at least partially attain a conventional dendritic form. A casting then produced will have a microstructure producing less than optimum physical properties.

According to the present invention, there is provided a process for injection moulding of articles from an alloy able to form a dendritic primary phase, wherein the process includes the steps of:

(a) providing at a nozzle a quantity of the alloy which is at least predominantly in a liquid state;

(b) moving the alloy along a flow path from the nozzle to a die cavity defined by a mould whereby the alloy is caused to flow along the flow path as a stream of alloy;

(c) controlling the alloy as it is moved along the flow path to increase the stream in transverse cross-sectional area along flow of the alloy between an inlet end and an outlet end of at least a part of the length of the flow path, thereby reducing the flow velocity of the alloy sufficiently in its flow through said part, from a sufficient flow velocity at the inlet end, whereby the alloy is caused to change from said at least predominantly liquid state to a semi-solid state; and

(d) moving the alloy into the die cavity in said semi-solid state.

The invention further provides a process for injection moulding of articles from an alloy able to form a dendritic primary phase, wherein the process includes the steps of:

(a) feeding the alloy into an extruder barrel which at one end terminates in a nozzle through which the interior of the barrel is in communication with a die cavity defined by a mould;

(b) forcing the alloy along the barrel, towards and into an accumulation chamber defined by the barrel adjacent to the nozzle, by rotation of an extruder screw in the barrel; and

(c) applying to alloy in the accumulation chamber a force for discharging alloy from the chamber, through the nozzle;

wherein the process further includes the steps of:

(d) controlling the condition of alloy in the chamber by:

(i) shearing the alloy by the rotation of the extruder screw, and

(ii) adjusting the temperature of the alloy,

whereby alloy in the accumulation chamber is at least predominantly in a liquid state;

(e) moving the alloy along a flow path from the nozzle to the die cavity and thereby causing the alloy to flow along the flow path as a stream of alloy;

(f) controlling the alloy as it is moved along at least a part of the length of the flow path to increase the stream in cross-sectional area in the direction of alloy flow, thereby reducing the flow velocity of the alloy sufficiently in its flow through said part, from a sufficient flow velocity at an upstream end of said part, whereby the alloy is caused to change from said at least predominantly liquid state to a semi-solid state.

The invention still further provides apparatus for injection moulding of articles from an alloy able to form a dendritic primary phase, wherein the apparatus includes:

(a) supply means for providing a quantity of the alloy which is at least predominantly in a liquid state at a nozzle;

(b) means for moving the alloy along a flow path defined between the nozzle and a die cavity defined by a mould whereby the alloy is caused to flow along the flow path as a stream of alloy;

(c) controlling means for controlling the alloy as it is moved along the flow path to increase the stream in transverse cross-sectional area along flow of the alloy between an inlet end and an outlet end of at least a part of the length of the flow path, and for thereby reducing the flow velocity of the alloy sufficiently in its flow through said part, from a sufficient flow velocity at the inlet end, whereby the alloy is caused to change from said at least predominantly liquid state to a semi-solid state; and

(d) means for moving the alloy into the die cavity in said semi-solid state.

Additionally, the invention provides apparatus for injection moulding of articles from an alloy able to form a dendritic primary phase, wherein the apparatus includes:

(a) an extruder barrel which has a nozzle at one end through which the interior of the barrel is in communication with a die cavity defined by a mould, an accumulation chamber defined by the barrel adjacent to the nozzle, and an inlet spaced from the one end;

(b) means for forcing the alloy along the barrel, towards and into the chamber; and

(c) means for discharging alloy from the chamber, through the nozzle;

wherein the apparatus further includes:

(d) control means operable to control the alloy state, said control means including:

 (i) means for shearing the alloy as it moves from the inlet towards the chamber, and

 (ii) means for adjusting the temperature of the alloy, whereby alloy in the accumulation chamber is at least predominantly in a liquid state;

(e) means for moving the alloy along a flow path from the nozzle to the die cavity and thereby causing the alloy to flow along the flow path as a stream of alloy;

(f) controlling means for controlling the alloy as it is moved along at least a part of the length of the flow path to increase the stream in cross-sectional area in the direction of alloy flow, for thereby reducing the flow velocity of the alloy sufficiently in its flow through said part from a sufficient flow velocity at an upstream end of said part, whereby the alloy is caused to change from said at least predominantly liquid state to a semi-solid state.

In the process of the invention, heat energy input to the alloy as it is moved through the barrel may be controlled so that, in flow of the alloy into the die cavity, the alloy has a substantially higher solids content whereby it is sufficiently semi-solid or thixotropic and has properties more similar to that of a liquid. The solids content of the alloy in its flow into the die cavity may be in excess of 35 volume %, such as, for example, from 40 to 65 volume %. As a consequence of the higher solids content of the alloy in its flow into the die cavity, the primary particles are

able to substantially retain their spheroidal degenerate dendrite form. Thus, with sufficient rapid solidification of the alloy after its injection into a die cavity, the primary particles are able to retain their small particle size, thereby providing a microstructure in which those particles are in a matrix of secondary phase, and which enhances the physical properties of the cast part. The particle size is able to be smaller than that produced in the Thixomat process as previously used.

In contrast to the solids content of in excess of 35 volume %, such as from 40 to 65 volume %, the alloy in the accumulation chamber is indicated as at least predominantly in a liquid state. The alloy in the accumulation chamber may be substantially, or completely in the liquid state and thus substantially, or completely, free of solids. However, alloy in the accumulation chamber may have some solids content and, while this may range up to about 20 volume%, it preferably is not more than 15 volume%.

As the alloy in the accumulation chamber is to have alloy which is at least predominantly in a liquid state, the present invention does not require close control over the temperature of alloy being moved along the barrel by the extruder screw. This is in marked contrast to the disclosure of USP 5040589 to Bradley et al.

To the extent that die cavity fill is achieved in the process of Bradley et al with alloy having a given level of solids content, this results from:

(i) shearing action generated by the extruder screw and temperature control generating or maintaining a required solids content in the alloy before it passes beyond the screw; and

(ii) temperature control for alloy received into the accumulation zone, without the benefit of further shearing action.

In contrast, the present invention does not require shearing action generated by the screw for the purpose of achieving a solids content. Rather, that action is simply to advance the alloy and the solids content need only be sufficient to enable the screw to advance the alloy. Also, in the invention, even that minimal solids content for alloy advancement need not be retained in alloy in the accumulation chamber. As a consequence of these matters temperature control requirements are less stringent, since the invention does not require temperature control to within a few degrees.

There of course are matters by which the present invention differs from the Thixomat process, such as in the form disclosed in USP 5040589. However the invention differs even more radically in achieving a change in state of the alloy after it passes beyond the nozzle, and in achieving a semi-solid state for the alloy with a desirable, relatively high solids content by control over alloy flow velocity.

In the process according to the present invention, the alloy supply may be in the form of pellets or chips of an alloy which, on heating, are able to attain a semi-solid state possessing thixotropic properties. However, this need not be the case. That is, the pellets or chips supplied to the barrel may be from a conventionally cast alloy and hence not reheatable to a semi-solid state in which the alloy possesses thixotropic properties. In either case, the process of the invention does not necessitate the level of control on the temperature of the alloy in its flow through the barrel to the accumulation chamber. Rather, the invention necessitates that, particularly in the accumulation chamber, the formation of dendritic primary particles is suppressed. The alloy in the accumulation chamber may, and preferably does, have not more than a relatively low solids content. Heat energy input to the alloy, in its movement through the barrel and during its residence time in the accumulation chamber, need only be consistent with suppression of dendritic primary particles. In contrast to the disclosure of Bradley et al, it is not necessary that, prior to the alloy reaching the accumulation chamber, the temperature of the alloy is controlled so as to attain and maintain a semi-solid state in which it possess thixotropic properties enabling it to flow like a liquid under applied force. Rather, in the process of the invention, such state is attained downstream of the accumulation chamber and, as a result, is able to be maintained in flow to the die cavity. As a consequence, alloy in the die cavity is able to solidify to achieve a microstructure having fine rounded or spheroidal degenerate dendrite primary particles in a lower melting point secondary phase or matrix. The microstructure is able to be achieved substantially throughout a resultant casting, with the primary particles substantially less than 40 μm in size. Those particles may be down to about 10 μm or less in size. Accordingly, the casting can have enhanced physical properties consistent with such microstructure.

In the present invention, the flow path for the alloy, from the nozzle to the die cavity, includes as the controlling means for controlling the alloy what is herein

referred to as a controlled expansion port (or CEP). This is a relatively short length of the alloy flow path which increases in cross-section from an inlet end, through to an outlet and, of the CEP. At the outlet end, the CEP may open to or within the die cavity, in an arrangement providing for casting by direct injection. While the outlet end preferably opens to the die cavity, there are circumstances where the form of the die cavity, in a region into which alloy first flows, is such that the region of the die cavity is able to define at least an outlet end part of the length of the CEP. That is, the CEP may be at least in part within, and defined by, the region of the die cavity.

In an alternative to such direct injection arrangement, alloy from the nozzle may flow through a sprue region to a runner. In that alternative, a CEP may be provided at the inlet or outlet end of the runner, or intermediate of a respective end of each of a first runner and a second runner. Any runner downstream of the CEP has a cross-section which is not less than the cross-section of the outlet end of the CEP. That is, the runner does not provide a constriction to flow of alloy from the outlet end of the CEP.

In the variants of that alternative to the direct injection arrangement, there may be a plurality of runners each receiving a respective portion of alloy flow from the sprue region. Each of the runners may provide alloy flow to a common die cavity or to a respective die cavity. With use of a plurality of runners, there may be a single CEP through which alloy flows to each runner, with each runner having a cross-section downstream of the single CEP which does not provide a significant constriction to the flow of the portion of the alloy it receives from the CEP. Alternatively, there may be a respective CEP for each of the plurality of runners, with each runner having a cross-section in its extent beyond the outlet end of its CEP which is not less than the cross-section of that outlet end.

In a direct injection arrangement, the flow of alloy from a screw auger or extruder screw to the die cavity may continue along the axis of the auger or screw. However, where a runner arrangement is provided for indirect injection, the or each runner most conveniently extends laterally with respect to that axis. Thus, the runner or runners may extend along a parting plane between separable parts of a die tool which defines the or each die cavity.

With use of a CEP, the state of an alloy in its flow therethrough is able to be modified. Thus, with an alloy having a solids content which is too low to

provide a semi-solid state possessing thixotropic properties, such state is able to be achieved during flow through the expansion section provided by the CEP and maintained with flow of alloy into the or each die cavity. For the state of the alloy to be changed to achieve a semi-solid state possessing thixotropic properties, it is highly desirable that the alloy have a flow velocity through the CEP which is relatively high, but decreases from the inlet end to the outlet end of the CEP. The range of suitable flow velocities varies, depending on the alloy in question. For a magnesium alloy the flow velocity at the inlet end preferably is an upper level for the CEP in excess of 60 m/s, such as from 140 to 165 m/s. For an aluminium alloy, the flow velocity at the inlet end preferably is an upper level for the CEP in excess of 40 m/s, preferably in excess of 50 m/s, such as from 80 to 120 m/s, for example from 80 to 110 m/s. For other non-ferrous alloys capable of being converted to a semi-solid state having thixotropic properties, such as zinc and copper alloys, the preferred range for inlet end flow velocities generally may be similar to that indicated for aluminium alloys but can vary somewhat with the unique characteristics of different alloys. The reduction in flow velocity most preferably is such as to achieve an alloy flow velocity at the outlet end of the CEP which is at a lower level of from about 50% to 80%, such as from 65% to 75%, of the flow velocity at the inlet end.

In order to achieve the indicated flow velocities at the inlet and outlet ends of the CEP, the cross-sectional area of the CEP at those ends needs to be related to the mass flow rate achieved by the apparatus. That is, for a given flow rate at which the alloy is moved along the flow path, the areas need to be such as to achieve the required reduction in flow velocity in flow of the alloy through the CEP. Where alloy is moved from the accumulation chamber by axially advancing the extruder screw, the rate of advance of the screw is determined by the required volume flow rate through the CEP.

The form of a CEP, beyond the requirement that it increases in cross-section from its inlet end to its outlet end, can vary substantially. The length of a CEP can be relatively short, such as from about 5 to about 20 mm, and preferably about 10 to 15 mm. However, the length of a CEP can vary with the alloy being cast and the size of a casting being produced, and it can range up to about 60 mm. At least where it is of shorter length, the CEP may be of circular cross-section. However, particularly where it opens to a die cavity or is at least in part

defined by and within a die cavity, other cross-sections such as rectangular can be used. A CEP may have an axis or centre line which is straight. However, a CEP can, if required, have an arcuate or bent axis or centre line, such that it provides a change in direction of alloy flow therethrough.

The physical form of a CEP can vary substantially. However, while not necessarily definitive of all CEP forms, empirical results indicate that a highly desirable feature of a CEP is able to be expressed in terms of the characteristics of alloy flow therethrough and, hence, the microstructure of alloy solidified in a CEP on completion of a casting operation. This feature of a CEP is explained more fully in the following description.

The desirable form for a CEP is one giving rise to filling of a die cavity by alloy in a required semi-solid state in which, while the alloy is sufficiently semi-solid or thixotropic, it possesses and provides filling of the die cavity by properties more similar to that of a liquid. Where this is the case, a desirable casting having a microstructure characterised by fine primary particles, consisting of degenerate dendrites in a lower melting point secondary phase or matrix, is able to be achieved by sufficiently rapid solidification of the casting. The primary particles have a form from the group of rounded, spheroidal, degenerate dendritic, and mixtures thereof. Also, in an optimum casting, such microstructure is obtained substantially fully throughout the casting. Usually, the primary degenerate dendrite particles are of the order of about 40 μm or less. The form and size of these particles, and their distribution substantially throughout the casting in the secondary phase or matrix, results in the casting having an excellent combination of physical properties.

Thus, a CEP has a principal benefit in achieving, for alloy flowing therethrough, a semi-solid state in which the alloy possesses thixotropic properties. However, a CEP has a further practical benefit due to its increasing cross-sectional area in the direction of alloy flow. Thus, by ensuring that alloy immediately upstream of the CEP is at a sufficiently high temperature, the alloy is able to solidify in the die cavity and back along the flow path to the CEP, to define a solid-liquid interface at or a short distance downstream of the inlet end of the CEP. On completion of a casting and solidification of alloy back to that interface, the screw is able to be retracted from the accumulation chamber, to withdraw liquid alloy from the interface. The casting, with attached runner/CEP metal, then

is able to be removed from the die cavity, with minimal risk of what is referred to in the disclosure of Bradley et al. as "drool". Thus, the CEP enables practice more akin to that used in high pressure die casting, and obviates the need to form a sealing plug of solidified metal as proposed in Bradley et al. Clearly, a plug of metal which does not separate with the casting presents potential problems during successive cycles of operation.

While not believed to be fully definitive of physical forms for a CEP, it is found that a CEP producing a desirable casting as detailed above may itself give rise to a specific microstructure in alloy solidifying in the CEP. As viewed in longitudinal sections of the CEP, this is characterized by at least a degree of fine striations or bands which extend transversely with respect to the direction of alloy flow through the CEP. These striations or bands are believed to result from concentration banding, such as due to alternating bands being concentrated with respect to the primary and the secondary phases. Thus, in the case of a magnesium alloy containing aluminium as a principal alloy element, alternate bands are relatively magnesium-rich and aluminium-rich, respectively. In optimum cases, the striations or banding extends substantially throughout the CEP, both substantially across its transverse extent and substantially along its full length.

Particularly where the CEP is at least in part defined within and by the die cavity, such striations or bands will be in the corresponding part of a casting. This can be undesirable, for a variety of reasons, at least where the striated or banded part of the casting is critical. This is because the part of the casting where this occurs has a different microstructure, possibly having less than desirable physical properties, than the main volume of the casting. In such cases, it is preferably that the CEP be located in a part of the die cavity providing a less critical part of the casting or that the casting be made with a CEP which opens to or upstream of the die cavity, rather than one defined at least in part by the die cavity.

At least in some instances, a CEP replaces a gate by which, in die casting apparatus or a Thixomat machine, a runner opens to a die cavity. This is most clearly the case where a CEP has its outlet opening to or within a die cavity. However, in contrast to a runner and gate arrangement, at least the outlet of a CEP may be, and preferably is, of larger cross-sectional area than its runner, or similar part of the alloy flow path, immediately upstream of the CEP. As will be

appreciated, this is the converse of the cross-sectional area relationship between a gate and its runner since a gate represents a constriction with respect to alloy flow from its runner. A gate provides a constriction such that the flow velocity of alloy passing through a gate is greater than the alloy flow velocity through a runner ending at the gate. In contrast, while the inlet end of a CEP may provide a constriction with respect to its runner, the alloy flow velocity decreases through the CEP without there being a gate or other constriction at or beyond the outlet end of the CEP.

Also, the alloy flow velocities through the outlet of a CEP, as detailed above, are high relative to flow velocities used in die casting or as disclosed by Bradley et al., particularly so in the case of the flow velocity range indicated for magnesium alloys. Thus, for a given force used to generate the metal flow velocities, the cross-sectional area required for a flow path in use of the present invention, at least immediately upstream of the inlet to a CEP, necessarily is less than runner cross-sectional areas used in die casting apparatus. The same relatively smaller cross-sectional area also applies in use of the present invention relative to cross-sectional areas used in conventional Thixomat apparatus immediately upstream of the gate opening to the die cavity.

In order that the invention can be more readily understood, description now is directed to the accompanying drawings, in which:

Figure 1 is a schematic sectional view illustrating an arrangement for conventional Thixomat apparatus;

Figure 2 is a sectional view, on an enlarged scale relative to Figure 1, showing a first form of apparatus modification for use in the present invention;

Figure 3 is similar to Figure 2, but illustrates an alternative form of apparatus modification from use in the present invention;

Figure 4 is a photomicrograph showing the microstructure of a representative casting able to be produced using the present invention; and

Figure 5 is a photomicrograph showing the microstructure of alloy solidified in a CEP in producing a casting having a microstructure of the form illustrated in Figure 4.

With reference to Figure 1, the apparatus 10 shown therein has an alloy feed system 12, a heating and conveying system 14, and a mould or die tool 16. The feed system 12 includes a hopper 18 mounted above an end of the system

14 which is remote from mould 16. The hopper 18 is able to hold a sufficient quantity of pellets of alloy 20 for a number of casting cycles. The open, frusto-conical base of hopper 18 communicates with a volumetric feeder device 22 of system 12, with device 22 operable to meter alloy pellets to system 14.

The system 14 includes an elongate, horizontally disposed barrel 24 which extends from feed system 12 to mould 16. At its end adjacent to mould 16, barrel 24 defines a nozzle 26 by which barrel 24 communicates with a die cavity 28 defined by mould 16. Within barrel 24, system 14 further includes an elongate screw 30 which has helical flights 31. Screw 30 is rotatable in barrel 24 by means of a drive system 32 located beyond the end of system 14 remote from mould 16, while it also is able to advance or retract axially in barrel 24 under the action of actuator 34.

The feeder device 22 feeds pellets of alloy 20 from hopper 18 to barrel 24. The pellets in barrel 24 are advanced along barrel 24, by the action of flights 31, forwards nozzle 26, as screw 30 is rotated by drive system 32. The pellets of alloy 20 supplied to hopper 18 may be produced from an ingot preformed so that it has a microstructure consisting of degenerate dendrites in a lower melting point secondary phase or matrix. The alloy 20 thus is able to be reheated to a semi-solid state in which it possesses thixotropic properties but, under an applied force, is capable of flow similar to a liquid. Reheating of alloy 20 in barrel 24 is achieved in part by shear forces generated in the alloy 20 by flights 31 as screw 30 is rotated. However, apparatus 10 includes means, represented schematically by helical resistance heating coil 33, for external heating of barrel 24 to increase the input of heat energy to assist in heating alloy 20 to the required semi-solid state. Thus, alloy 20 progressively is converted from pellets to a slurry. However, the alloy, if provided as pellets, can be in a dendritic form, while it alternatively can be substantially molten alloy which preferably has at least a minimum solids content to facilitate its advance by screw 30.

The alloy 20, after collecting in accumulation chamber 35, is able to be forced through a bore 36 defined by nozzle 26, into die cavity 28 of mould 16, by advancing screw 30. From bore 36, the slurry flows through a main runner 38 and then a secondary runner 39, each defined by a fixed die tool 40 of mould 16, and finally through a gate to die cavity 28. With the completion of alloy injection into cavity 28, alloy solidification in cavity 28 progresses back to a required solid-slurry

interface adjacent to the junction of bore 36 and runner 38. Screw 30 then is retracted to slightly retract the slurry from the interface, and movable die tool 41 of mould 16 is retracted from die tool 40, to enable a cast product with attached runner metal to be removed from mould 16.

Operation with apparatus 10 enables the production of castings which are suitable for many applications. This applies whether alloy 20 is supplied as pellets or molten alloy and, if as pellets, whether or not the pellets have a microstructure consisting of degenerate dendrites in a lower melting point phase or matrix. That is, the castings can be suitable for many applications, whether or not the alloy is able to be reheated to a semi-solid state in which it possesses thixotropic properties but is capable of flow as a liquid under an applied force. However, in each case, the present invention enables the microstructure of the castings to be enhanced to thereby improve physical properties of the castings. Also, the invention enables the range of castings to be extended to include those for which such improved properties are essential.

Figure 2 illustrates one arrangement for modification of apparatus 10 of Figure 1. In Figure 2, parts corresponding to those of Figure 1 have the same reference numeral, plus 100. Thus in the detail shown, it can be seen that apparatus 110 of Figure 2 has a screw 130 rotatable in barrel 124, to advance alloy to accumulation chamber 135. Screw 130 also is axially movable to force alloy in chamber 135 through nozzle 126. From nozzle 126, the alloy is injected, via heated nozzle 50, into die cavities 128 defined by the tools 140, 141 of mould 116.

The modification of Figure 2 involves the provision of an electrically heatable nozzle or extension 50 mounted between the outlet end of bore 136 of nozzle 126 and a respective secondary runner 139 for each die cavity 128. The nozzle 50 defines a bore 52 which provides a continuation of bore 136 and communicates with each secondary runner 139. Thus, bore 52 of nozzle 50 serves a similar function to main runner 38 of Figure 1.

The nozzle 50 defines a frusto-conical seat 54 which leads to the inlet end of its bore 52. The outlet end of nozzle 126 has a complementary frusto-conical external surface which provides a seal against seat 54. The external surface of nozzle 50 is stepped to define a peripheral flange 56 around the inlet end of bore 52, an intermediate portion 58 which extends from flange 56 over a major part of

the length of bore 52 and a small diameter terminal end portion 60 around the outlet end of bore 52. The fixed die tool 140 of mould 116 defines a somewhat similarly stepped recess 62 in which nozzle 50 is mounted, with flange 56 and end portion 60 being a firm friction fit in recess 62. However, intermediate portion 58 of nozzle 50 is of lesser diameter than the corresponding part of recess 62, so as to define an insulating annular air-gap 64 therebetween. Around intermediate portion 58 of nozzle, an electrical induction or resistance heating coil 66 is provided, in air-gap 64, to enable controlled heating of nozzle 50, while a sheath of insulation 68 is provided around coil 66, against the wall of recess 62, to minimise loss of heat energy to die tool 140.

The arrangement shown in Figure 2 shows bore 52 of nozzle 50 as having a reduced size at its outlet end. This is highly desirable but, in an alternative arrangement, bore 52 may be of constant form throughout its full length, as with main runner 38 of Figure 1. In the arrangement shown, bore 52 is of constant cross-section along a major part of its length, over which it provides a continuation of the cross-section of bore 136 of nozzle 126. However, beyond that major part of its length, in the direction of alloy flow therethrough from nozzle 126, bore 52 has a part 70 which tapers frusto-conically to a minimum cross-section at a constriction 71, and thereafter has a part 72 which tapers frusto-conically to a cross-section at the outlet end which is larger than that at constriction 71. The part 72 comprises a controlled expansion port (or CEP) as detailed herein, while the constriction 71 is to define the location of an interface between alloy which has solidified on completion of a casting operation and alloy which is still partly in a liquid state. That is, constriction 71 establishes the interface back to which alloy solidifies to give rise to metal which separates with a casting.

The arrangement of Figure 2 is intended to comprise part of apparatus which, apart from the differences described with reference to Figure 2, is similar to the apparatus of Figure 1. In use of such apparatus, the alloy supplied as pellets or chips to the hopper may have a microstructure such that the alloy is heatable to a semi-solid state possessing thixotropic properties but is able to flow as if a liquid under the applied force generated by the auger. However, it is not necessary that such pre-prepared alloy be used. That is the alloy, if in the form of chips or pellets, may have a conventional cast or even a wrought microstructure in which the primary phase is present in a dendritic form. Thus, in the latter case, the alloy

is able to be heated to a semi-solid state, but not such as to inherently possess thixotropic properties in that state. With alloy having either type of microstructure, the alloy of the pellets or chips are heated under the action of screw 130, by strain energy imparted by flights 131 of screw 130, to form a semi-solid slurry. However, the alloy alternatively may be supplied in substantially molten form, such as with a low solids content.

With each alloy microstructure, or with substantially molten alloy, it is not necessary to ensure that heating is controlled so as to achieve a solids content of in excess of 35 volume %, such as from 40 to 65 volume %. The solids content can fall below that at which an alloy heatable to a thixotropic state will retain that state, that is, below about 30 volume % solids content. Similarly, the alloy having a conventional microstructure also can be heated to a solids content below about 30 volume %, although, in attaining this level, it may not pass through a stage in which it exhibits thixotropic properties. In each case, as with substantially fully molten alloy, a low solids content is permissible because the alloy, in each case, will attain a higher required solids content and a state in which it possesses thixotropic properties, due to the action of the CEP defined by part 72 of the bore 52 of nozzle 50.

In attaining a low solids content, with alloy of either microstructure, at least some of the primary phase will melt. Thus, with the prepared alloy having a microstructure with degenerate dendrite particles, these particles will be reduced in size to smaller rounded particles. With the non-prepared alloy having a microstructure with dendritic primary phase, these particles also will be reduced in size. In the latter case, the reduction in size initially will be by loss of dendrite arms and branches, with the particles reducing essentially to rounded residual particles. Also, in each case, the reduction in solids content to less than 30 volume %, can, in fact, progress to the stage at which the alloy essentially comprises liquid phase. That is, each alloy may be substantially fully melted, if not in this condition from the outset.

In the CEP, the alloy is caused to undergo a substantial change in its flow regime. The increasing cross-sectional area of the CEP between the inlet and outlet causes a reduction in alloy flow velocity to within a preferred range of 50 to 80%, such as from 65 to 75%, of the flow velocity at the inlet of the CEP. The effective cross-sectional area of the CEP at its outlet end preferably is from two to

four times greater than the cross-sectional area of the inlet end of the CEP or immediately upstream of the CEP relative to the alloy flow direction. As indicated above, the alloy flow velocity through the inlet end of a CEP is relatively high, such as in excess of 60 m/s, preferably from 140 to 165 m/s for a magnesium alloy and in excess of 40 m/s, preferably in excess of 50 m/s, such as from 80 to 120 m/s, for example from 80 to 110 m/s, for aluminium and other alloys; with the outlet end flow velocity from about 50% to 80%, such as from 65% to 75%, of the inlet end flow velocity. Also, the flow path between the inlet and outlet of a CEP preferably is relatively short, such as from 5 to 20 mm, and preferably from 10 to 15 mm, such that the residence time for alloy in a CEP is very short, such as from about 60 to 100 µs for magnesium alloy flowing through the outlet end of a CEP at a preferred flow velocity. However, depending on the alloy and size of casting being produced, a longer CEP such as up to about 60 mm in length can be appropriate.

The rapid reduction in flow velocity of alloy in the CEP is found to be capable of generating high pressure waves in the alloy. The form of the CEP, for a given alloy, most preferably is chosen to ensure that such pressure waves are generated. Computer simulations of flow through a CEP have indicated that pressure waves of about ± 400 MPa can be generated. It is known that pressure differences of the order of a few 100kPa can cause separation of less and more dense elements of an alloy, such as magnesium and aluminium. The computer simulations therefore point to pronounced separation, with migration of a less dense element to high pressure pulses and of a higher density element to low pressure pulses. Moreover, the computer simulations suggest that the pressure waves will have a wavelength of about 40 µm for a magnesium alloy.

The results of the computer simulation are found to be supported by examination of microstructures achieved with use of a suitable CEP. On completion of a casting operation, relatively rapid solidification of the alloy in and back from each die 128 cavity, is able to continue along each runner 139 and through the CEP of bore part 72 to a solid-liquid interface at or just short of the constriction at 71. With such solidification, the microstructure of alloy solidified in the CEP is found to exhibit transverse striations or bands resulting from alloy element separation. The microstructure is found to have successive bands richer in respective elements of the alloy, due to segregation on the basis of density,

indicating generation of intense pressure waves in alloy in its flow through the CEP. The bands are found to have a wavelength of the order of 40 μm for a magnesium alloy, indicative of pressure waves of about ± 400 MPa. However, with aluminium alloys, the wavelength is found to be about 200 μm, with other alloys except magnesium alloys being similar. Moreover, the banding to a substantial degree involves segregation of primary and secondary phases. Thus, in the case of a magnesium alloy containing aluminium as a principal alloy element, there is obtained alternate magnesium-rich and aluminium-rich bands, with these respectively being dendrite rich and secondary phase rich. Within aluminium-rich bands, there is found to be an excess of secondary phase intermetallics such as $Mg_{17} Al_{12}$. Moreover, the magnesium-rich bands are found to contain primary phase as rounded degenerate dendrite particles substantially smaller in size than 40 μm, such as about 10 μm.

The striations or bands generally extend across the full lateral extent of the CEP, substantially at right angles to the alloy flow direction. Also, they generally are evident along the full length of the CEP in that direction.

The cross-sectional area of a CEP at its inlet end, and of the metal flow path upstream from that end, preferably is small in relation to the cross-sectional area of a runner used in producing a casting of a given size by a die casting process. The cross-sectional area of the inlet end of a CEP and the fluid flow path upstream from that end also generally is less than the cross-sectional area of the bore of the nozzle of Thixomat apparatus. Thus, in use of the present invention, it is preferred that the nozzle of the apparatus be modified to a form having a bore of smaller cross-section.

Thus, with use of the arrangement of Figure 2, it is not necessary that heating elements provided around barrel 124 be such as to bring the alloy to a temperature at which it achieves a semi-solid state in which it possesses thixotropic properties. In such state, the alloy would be able to flow like a liquid under forces generated by rotation of screw 130 in moving the alloy into the accumulation chamber 135 and by axial movement of screw 130 in forcing the alloy from chamber 135 and through bore 136 of nozzle 126. Rather, the arrangement of Figure 2 enables less precise heating in which the alloy is maintained at a relatively low solids content, at a temperature at which growth of dendritic primary particles is suppressed. Also, of course, shear generated by

rotation of screw 130 ensures that such primary particles that are present are degenerate dendritic particles of rounded or spheroidal form and of a small particle size. As a consequence, alloy in chamber 135 readily is able to be forced through bore 136, and through the CEP defined by bore part 72.

The heating coil 66 can assist in maintaining the alloy in a suitable state up to the stage of its flow through the CEP. However, coil 66 has a further function. The semi-liquid state of the alloy in which it has thixotropic properties, attained in its flow through the CEP, is able to be retained by the alloy during the filling of each die cavity 128. For optimum properties in the casting produced in each cavity 128, the mould 116 preferably provides for relatively rapid solidification of alloy in each cavity, such that substantially throughout each casting it has a microstructure having fine rounded or spheroidal degenerate dendrite primary particles in a secondary phase or matrix. To assist in achieving this, the solidification with such microstructure preferably progresses back to the CEP to achieve a somewhat similar microstructure in alloy solidified in the CEP. However, the microstructure obtained in a CEP of preferred form also is characterised by transverse striations or bands as detailed above. In both the casting and the CEP, the primary particles preferably are substantially less than 40 µm, such as about 10 µm or less.

Solidification of alloy back into the CEP is assisted by terminal end portion 60 of nozzle 50 being a friction fit in recess 52 of die tool 140, such that there is good thermal conduction from portion 160 to die tool 140. Thus, with die tools 140, 141 of mould 116 being such as to provide for rapid solidification of alloy in each die cavity 128, die tool 140 needs to be at a relatively low temperature such that it extracts heat energy from end portion 60. This assists in solidification of alloy in the CEP. However, intermediate portion 58 of nozzle 50 is insulated from die tool 140, other than for a degree of heat energy loss through portion 60, by provision of air-gap 64 and insulation sheath 68. It is in this context that heating coil 66 serves a further function. Coil 66 principally provides heat energy to intermediate portion 58 of nozzle 50. It is used to ensure that alloy in bore 52, upstream from the constriction 71, is maintained at a temperature to enable solidification of alloy in the CEP to progress back to a solid-liquid interface at or slightly downstream of constriction 71, as detailed above. Thus, on retraction of screw 130 on completion of a casting cycle, liquid alloy is able to be retracted

from that interface sufficiently to enable the solidified metal to be removed with the castings, upon opening of mould 116.

Turning now to Figure 3, the arrangement shown therein is similar in many respects to that of Figure 2. Thus, corresponding parts have the same reference numeral, plus 100.

In the detail shown it can be seen that apparatus 210 of Figure 3 has a screw 230 rotatable in barrel 224 to advance alloy to accumulation chamber 235. Screw 230 also is axially movable to force alloy in chamber 235 through nozzle 226. From nozzle 226, the alloy is injected into a die cavity 228 defined by the tools 240, 241 of mould 216.

The arrangement of Figure 3 has a nozzle or extension 150 mounted between the outlet end of bore 236 of nozzle 226 and a runner 239 for the die cavity 228. The nozzle 150 defines a bore 152 which provides a continuation of bore 236 and communicates with the runner 239. Thus, bore 152 of nozzle 150 serves a similar function to main runner 38 of Figure 1.

The nozzle 150 defines a frusto-conical inlet portion 80 which defines the inlet end of its bore 152. The outlet end of nozzle 226 defines a complementary frusto-conical recess 82 which provides a seat in which portion 80 provides a seal. The external surface of nozzle 150 is stepped to define a peripheral flange 84 which is beyond the inlet portion 80 and which is a friction fit in recess 85 defined by fixed platen 86, beyond nozzle 226. Also, the outlet end of nozzle 150 is tapered and provides a seal in a complementary recess 89 defined by fixed die tool 240 of mould 216.

The arrangement shown in Figure 3 shows bore 152 of nozzle 150 as having a reduced size at its outlet end. This is highly desirable but, in an alternative arrangement, bore 52 may be of constant form throughout its full length, as with main runner 38 of Figure 1. In the arrangement shown, bore 152 is of constant cross-section along a part of its length, over which it provides a continuation of the cross-section of bore 236 of nozzle 226. However, beyond that part of its length, in the direction of alloy flow therethrough from nozzle 226, bore 152 has a part 170 which tapers frusto-conically to a minimum cross-section at constriction 171, and thereafter has a part 172 which tapers frusto-conically to cross-section at the outlet end which is larger than that at constriction 171. The part 172 comprises a controlled expansion port (or CEP) as detailed herein, while

the constriction 171 is to define the location of an interface between alloy which has solidified on completion of casting operation and alloy which is still partly in a liquid state. That is, constriction 171 establishes the interface back to which alloy solidifies to give rise to metal which separates with a casting.

Operation with apparatus 20 of Figure 3 is similar to that described with reference to apparatus 110 of Figure 2. A principal difference is that nozzle 150 of apparatus 210 is not provided with a separate heating coil, while it is in good surface to surface contact at respective parts with each of nozzle 236, fixed platen 86 and die tool 240. The arrangement is such that a sufficient thermal gradient is able to be established between the inlet and outlet ends of nozzle 150 to achieve a solid-liquid interface at or adjacent to constriction 171 when, on completion of a casting cycle, alloy solidifies in the die cavity 128 and back into the CEP defined in part 172 of the bore 152 of nozzle 150. This is able to be achieved by heat energy provided at the inlet end from nozzle 226, and heat energy extracted at the outlet end by die tool 240. It also may be necessary for heat energy to be extracted via flange 84 by fixed platen 86, and for an insulating sheath to be provided between nozzle 226 and platen 86.

Nozzle 150 of the arrangement of Figure 3 may be made of a suitable metal or ceramic. Nozzle 50 of Figure 2 preferably is made of a suitable metal, although it may have a ceramic coating.

It is indicated above that nozzle 50 of Figure 2 may have a bore 52 of constant cross-section throughout, while the same is indicated for bore 152 of nozzle 150 of Figure 3. However, in each case, this requires that a suitable CEP is provided in the alloy flow path downstream of the respective nozzle.

Figure 4 is a photomicrograph illustrating a typical microstructure of a casting produced with use of the present invention, from AZ91 magnesium alloy. This microstructure shows fine, rounded or spheroidal degenerate dendrite cells substantially less than 10 μm in size and occupying up to 60% of the volume fraction. Each dendrite cell contains concentration rings showing a fluctuating, somewhat decaying sinusoidal ratio of constituent alloy elements. Between the dendrite cells, there is solidified metal of eutectic composition, with the fineness of the eutectic structure difficult to resolve despite the level of magnification used.

Figure 5 is a photomicrograph of the microstructure of AZ91 magnesium alloy solidified in a CEP, in producing a casting such as illustrated in Figure 4.

The direction of alloy flow through the CEP is shown by an arrow. The photomicrograph shows banding or striations extending transversely with respect to the flow direction. While not very readily discernible in this instance, the bands or striations as shown by X-ray analysis using secondary electron microscopy result from segregation of the parent metal magnesium and alloy additive elements such as aluminium. This segregation occurs due to intense pressure waves generated in the CEP by the reduction in alloy flow velocity as it flows through the CEP. The dynamic environment provided by the pressure waves is believed to lead to nucleation of primary particles of the parent metal at relatively high temperatures. Alternate bands are found to have a higher percentage of parent metal and a higher solidification temperature than would be expected for the starting alloy, relative to primary particles obtained in sprue/runner metal obtained by conventional pressure die casting. Similarly, the secondary phase rich intervening bands have a higher percentage of alloy elements and a lower solidification temperature than expected for the alloy, relative to secondary phases obtained in sprue/runner metal of conventional die casting. The microstructure is characterised by fine primary particles substantially smaller than 10 μm in a secondary phase matrix, with a banding wavelength of about 40 μm.

Finally, it is to be understood that various alterations, modifications and/or additions may be introduced into the constructions and arrangements of parts previously described without departing from the spirit or ambit of the invention.

CLAIMS:

1. A process for injection moulding of articles from an alloy able to form a dendritic primary phase, wherein the process includes the steps of:

(a) providing at a nozzle a quantity of the alloy which is at least predominantly in a liquid state;

(b) moving the alloy along a flow path from the nozzle to a die cavity defined by a mould whereby the alloy is caused to flow along the flow path as a stream of alloy;

(c) controlling the alloy as it is moved along the flow path to increase the stream in transverse cross-sectional area along flow of the alloy between an inlet end and an outlet end of at least a part of the length of the flow path, thereby reducing the flow velocity of the alloy sufficiently in its flow through said part, from a sufficient flow velocity at the inlet end, whereby the alloy is caused to change from said at least predominantly liquid state to a semi-solid state; and

(d) moving the alloy into the die cavity in said semi-solid state.

2. A process for injection moulding of articles from an alloy able to form a dendritic primary phase, wherein the process includes the steps of:

(a) feeding the alloy into an extruder barrel which at one end terminates in a nozzle through which the interior of the barrel is in communication with a die cavity defined by a mould;

(b) forcing the alloy along the barrel, towards and into an accumulation chamber defined by the barrel adjacent to the nozzle, by rotation of an extruder screw in the barrel; and

(c) applying to alloy in the accumulation chamber a force for discharging alloy from the chamber, through the nozzle;

wherein the process further includes the steps of:

(d) controlling the condition of alloy in the chamber by:

(i) shearing the alloy by the rotation of the extruder screw, and

(ii) adjusting the temperature of the alloy,

whereby alloy in the accumulation chamber is at least predominantly in a liquid state;

(e) moving the alloy along a flow path from the nozzle to the die cavity and thereby causing the alloy to flow along the flow path as a stream of alloy;

(f) controlling the alloy as it is moved along at least a part of the length of the flow path to increase the stream in cross-sectional area in the direction of alloy flow, thereby reducing the flow velocity of the alloy sufficiently in its flow through said part, from a sufficient flow velocity at an upstream end of said part, whereby the alloy is caused to change from said at least predominantly liquid state to a semi-solid state.

3. The process of claim 2, wherein the alloy is moved into the die cavity in said semi-solid state.

4. The process of any one of claims 1 to 3, wherein the alloy is in said semi-solid state substantially throughout filling of the die cavity.

5. The process of any one of claims 1 to 4, wherein the alloy when in the accumulation chamber has a solids content of not more than 20 volume %.

6. The process of claim 5, wherein the solids content is not more than 15 volume %.

7. The process of any one of claims 1 to 4, wherein the alloy when in the accumulation chamber is substantially free of solids.

8. The process of any one of claims 1 to 7, wherein the alloy is a magnesium alloy, and wherein the alloy is reduced in flow velocity from an upper level in excess of 60 m/s to a lower level of from about 50% to 80% of said upper level.

9. The process of claim 8, wherein the upper level is from 140 m/s to 165 m/s.

10. The process of claim 8 or claim 9, wherein the lower level is from 65% to 75% of the upper level.

11. The process of any one of claims 1 to 7, wherein the alloy is a non-ferrous alloy other than a magnesium alloy, and wherein the alloy is reduced in flow velocity from an upper level in excess of 40 m/s to a lower level of from about 50% to 80% of the upper level.

12. The process of claim 11, wherein the upper level is from 80 m/s to 120 m/s.

13. The process of claim 11 or claim 12, wherein the lower level is from 65% to 75% of the upper level.

14. The process of any one of claims 1 to 13, wherein the alloy, after changing to the semi-solid state, has a solids content in excess of 35 volume %.

15. The process of any one of claims 1 to 13, wherein the alloy, after changing to the semi-solid state, has a solids content of from 40 to 65 volume %.

16. Apparatus for injection moulding of articles from an alloy able to form a dendritic primary phase, wherein the apparatus includes:

(a) supply means for providing a quantity of the alloy which is at least predominantly in a liquid state at a nozzle;

(b) means for moving the alloy along a flow path defined between the nozzle and a die cavity defined by a mould whereby the alloy is caused to flow along the flow path as a stream of alloy;

(c) controlling means for controlling the alloy as it is moved along the flow path to increase the stream in transverse cross-sectional area along flow of the alloy between an inlet end and an outlet end of at least a part of the length of the flow path, and for thereby reducing the flow velocity of the alloy sufficiently in its flow through said part, from a sufficient flow velocity at the inlet end, whereby the alloy is caused to change from said at least predominantly liquid state to a semi-solid state; and

(d) means for moving the alloy into the die cavity in said semi-solid state.

17. Apparatus for injection moulding of articles from an alloy able to form a dendritic primary phase, wherein the apparatus includes:

(a) an extruder barrel which has a nozzle at one end through which the interior of the barrel is in communication with a die cavity defined by a mould, an accumulation chamber defined by the barrel adjacent to the nozzle, and an inlet spaced from the one end;

(b) means for forcing the alloy along the barrel, towards and into the chamber; and

(c) means for discharging alloy from the chamber, through the nozzle;

wherein the apparatus further includes:

(d) control means operable to control the alloy state, said control means including:

(i) means for shearing the alloy as it moves from the inlet towards the chamber, and

(ii) means for adjusting the temperature of the alloy,

whereby alloy in the accumulation chamber is at least predominantly in a liquid state;

(e) means for moving the alloy along a flow path from the nozzle to the die cavity and thereby causing the alloy to flow along the flow path as a stream of alloy;

(f) controlling means for controlling the alloy as it is moved along at least a part of the length of the flow path to increase the stream in cross-sectional area in the direction of alloy flow, for thereby reducing the flow velocity of the alloy sufficiently in its flow through said part from a sufficient flow velocity at an upstream end of said part, whereby the alloy is caused to change from said at least predominantly liquid state to a semi-solid state.

18. The apparatus of claim 17, wherein the means for moving the alloy along the flow path is operable to move the alloy into the die cavity in said semi-solid state.

19. The apparatus of any one of claims 16 to 18, wherein the controlling means comprises a controlled expansion port (CEP) which defines said at least part of the length of the flow port; the CEP has an inlet end and an outlet end between which it increases in cross-sectional area for controlling the alloy to increase the stream in cross-sectional area; and wherein the CEP is for use in injection

moulding of articles of a magnesium alloy and has a cross-sectional area at its inlet end such that, for a mass flow rate at which moving means is operable to move alloy along the flow path, the cross-sectional area of the inlet end of the CEP is such as to establish a flow velocity therethrough in excess of 40 m/s and the cross-sectional area of the outlet end of the CEP is such as to establish a flow velocity therethrough of from about 50% to 80% of that through the inlet end.

20. The apparatus of claim 19, wherein the cross-sectional area of the inlet end is such as to establish a flow velocity therethrough from 140 m/s to 165 m/s.

21. The apparatus of claim 19 or claim 20, wherein the cross-sectional area of the outlet end is such as to establish a flow velocity therethrough of from 65% to 75% of that through the inlet end.

22. The apparatus of any one of claims 16 to 18, wherein the controlling means comprises a controlled expansion port (CEP) which defines said at least part of the length of the flow port; the CEP has an inlet end and an outlet end between which it increases in cross-sectional area for controlling the alloy to increase the stream in cross-sectional area; and wherein the CEP is for use in injection moulding of articles of a non-ferrous alloy other than a magnesium alloy and has a cross-sectional area at its inlet end such that, for a mass flow rate at which moving means is operable to move alloy along the flow path, the cross-sectional area of the inlet end of the CEP is such as to establish a flow velocity therethrough in excess of 40 m/s and the cross-sectional area of the outlet end of the CEP is such as to establish a flow velocity therethrough of from about 50% to 80% of that through the inlet end.

23. The apparatus of claim 22, wherein the cross-sectional area of the inlet end is such as to establish a flow velocity therethrough from 80 m/s to 120 m/s.

24. The apparatus of claim 22 or claim 23, wherein the cross-sectional area of the outlet end is such as to establish a flow velocity therethrough of from 65% to 75% of that through the inlet end.

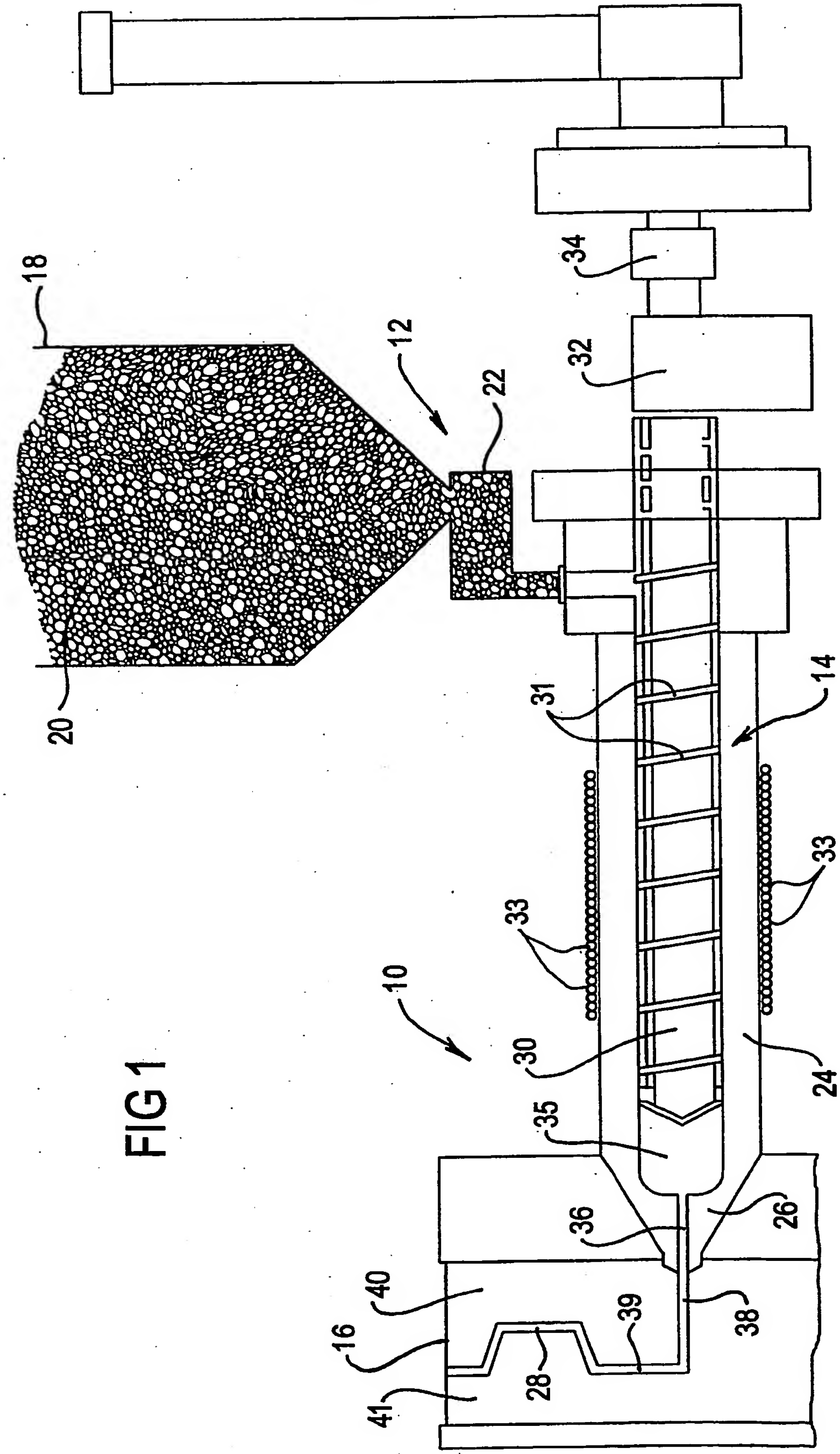

FIG 1

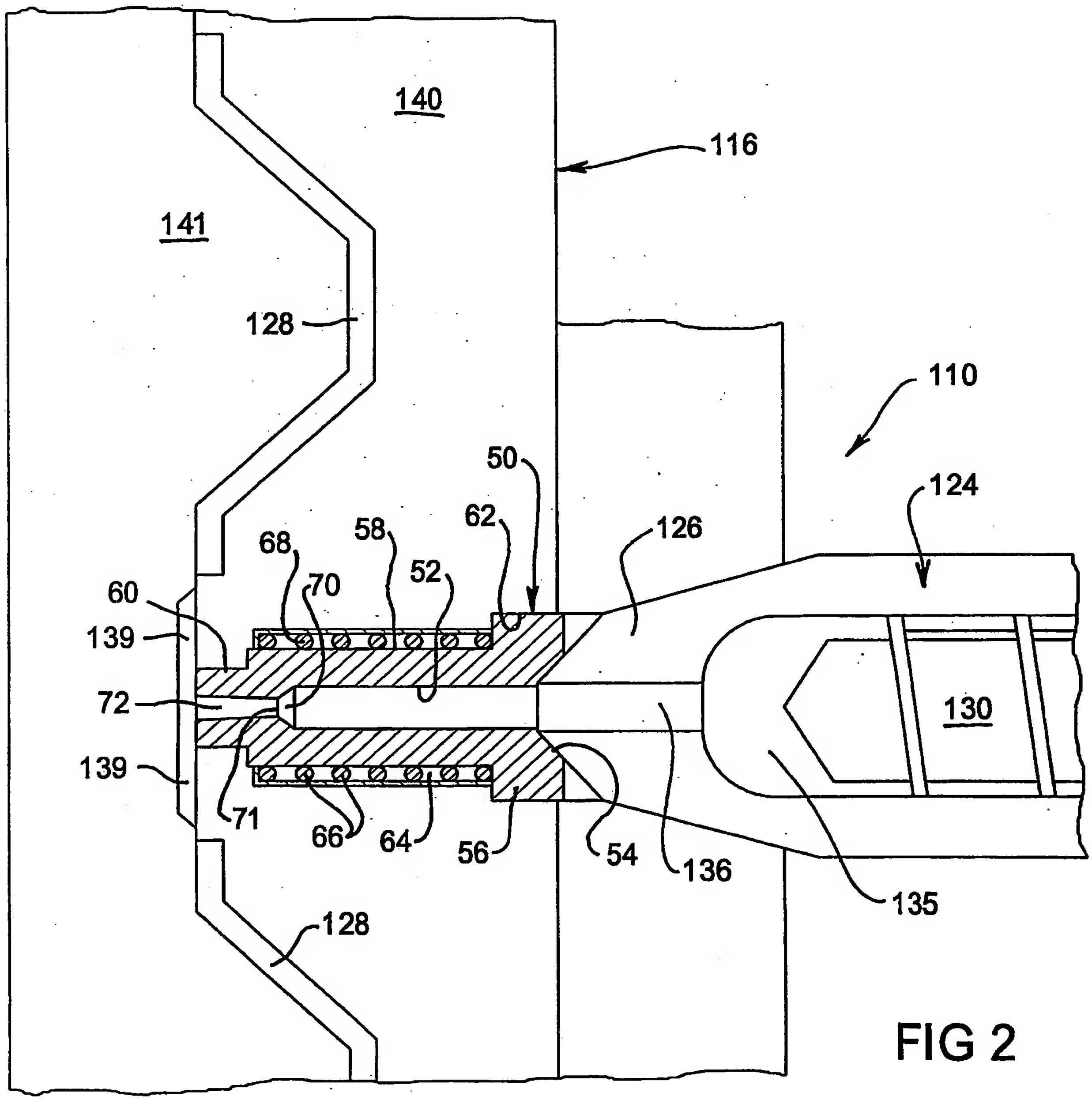

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FIG 2

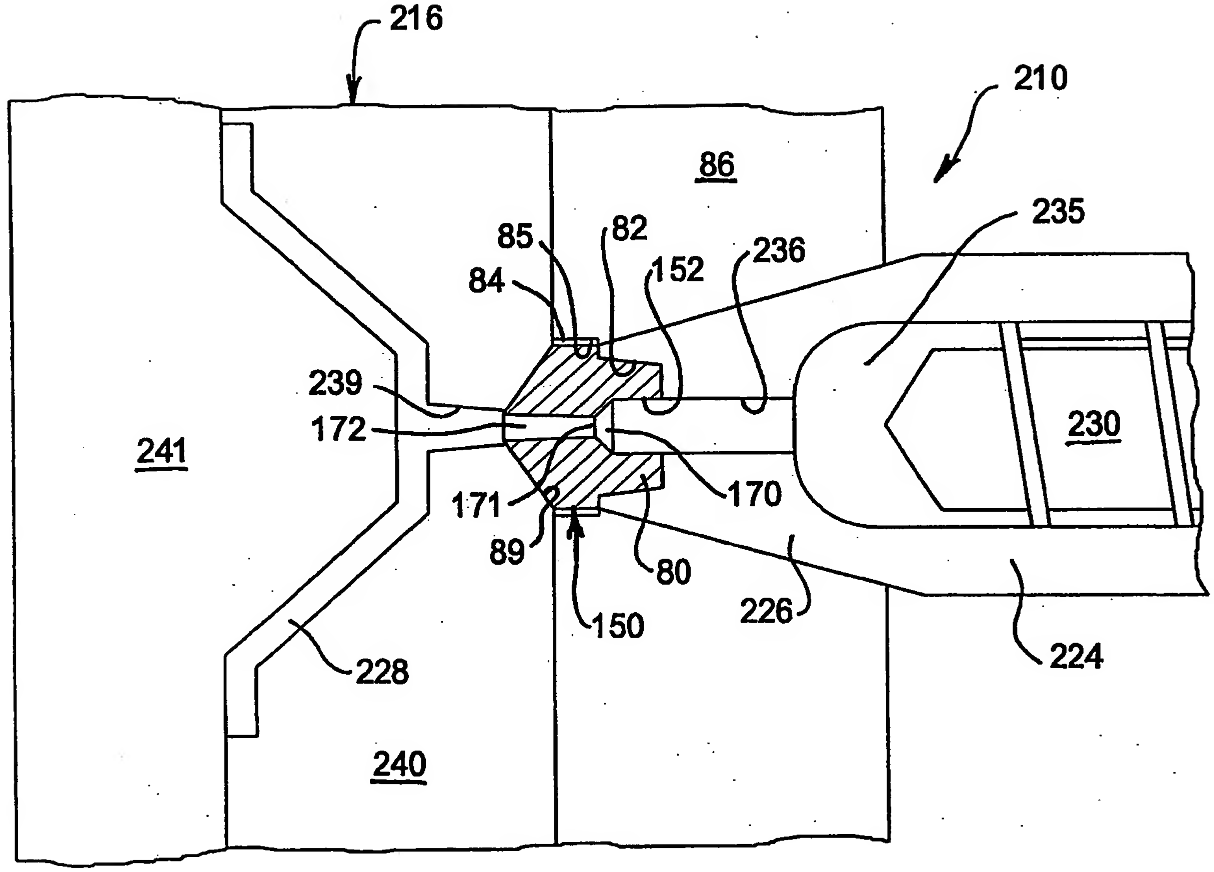
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FIG 3

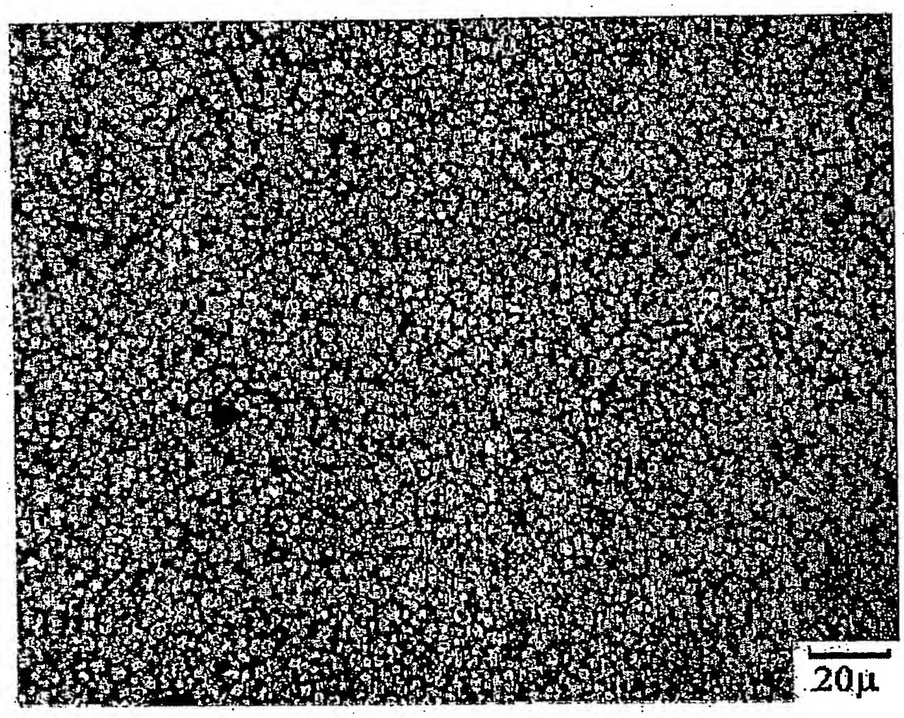

FIG 4

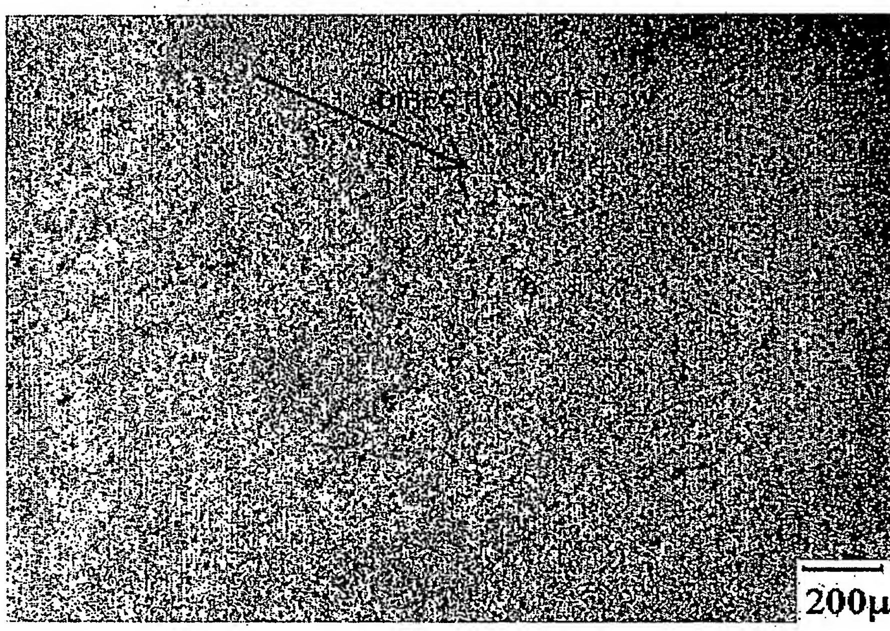

FIG 5

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU02/01137

A. CLASSIFICATION OF SUBJECT MATTER	
Int. Cl. 7:	B22D 17/20
According to International Patent Classification (IPC) or to both national classification and IPC	
B. FIELDS SEARCHED	
Minimum documentation searched (classification system followed by classification symbols)	IPC7 as above and B22D 17/00, 17/02, 17/04, 17/06, 17/08, 17/10, 17/12
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched	
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)	Derwent WPAT: IPC7 as above and B22D 17/00, 17/02, 17/04, 17/06, 17/08, 17/10, 17/12 and (expan+ or taper+ or section+)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P, X	WO 2002/30596 A1 (C. S. I. R. O.) 18 April 2002 Whole Document	1 to 24
P, X	WO 2002/16062 A1 (C. S. I. R. O.) 28 February 2002 Whole Document	1 to 24
X	WO 1995/34393 A1 (Cornell Research Foundation Inc) 21 December 1995 Whole Document	1 to 24

[X] Further documents are listed in the continuation of Box C [X] See patent family annex

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search 20 September 2002	Date of mailing of the international search report 27 SEP 2002
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA E-mail address: pct@ipaustralia.gov.au Facsimile No. (02) 6285 3929	Authorized officer DAVID K. BELL Telephone No : (02) 6283 2309

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU02/01137

C (Continuation).	DOCUMENTS CONSIDERED TO BE RELEVANT	
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 1999/28065 A1 (C. S. I. R. O.) 10 June 1999 Whole Document	
A	Patent Abstracts of Japan JP 2000-317603 A (Matsushita Electric Ind Co Ltd) 21 November 2000 Abstract	
A	Patent Abstracts of Japan JP 2001-071108 A (Nissan Motor Co Ltd) 21 March 2001 Abstract	

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/AU02/01137

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
WO	200230596	AU	20000763	AU	200195269		
WO	200216062	AU	20009678	AU	200181596		
WO	9534393	EP	765198	US	5501266		
WO	9928065	AU	14764/99	BR	9814706	CA	2310408
		EP	1137503	NO	20002706	PL	342005
		ZA	9810933				
JP	2001071108	NONE					
JP	2001317603						

END OF ANNEX